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COMMUNICATION

Discharge Onset Voltage Prediction For A Gas-Insulated System via The Figure-Of-Merit Concept

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ABSTRACT

The accuracy of discharge onset prediction via the figure-of-merit concept for a strongly electronegative gas is examined. A coaxial system is employed, for which the inner electrode possesses a surface roughness of $R_{\alpha}=35$ µm. With SF_6 as the insulating medium a reference discharge-onset characteristic is obtained for gas pressures up to 0.8 MPa. From a knowledge of this onset characteristic, the direct calculation of discharge onset voltages in other strongly electronegative gases is undertaken by utilizing the figure-of-merit concept. For gas pressures in the range $0.02<p<0.8$ MPa, the voltage values predicted are found to concur with the experimentally determined data.

INTRODUCTION

One of the notable advances in the design of power apparatus results from the application of the electronegative gas SF_6 as an insulating medium. A comprehensive review of the basic developments in this area is available in the literature [1].

At present the dielectric properties of many other strongly electronegative gases are under study [2,3]. This activity is given impetus by the advantages which would accrue through the application of a gas or gas mixture with insulation characteristics superior to compressed SF_6. Under practical conditions, and assuming acceptable economic and chemical behavior, this would imply that the particular gas or gas mixture should be less sensitive to the deleterious effects of electrode surface roughness or moving particles upon the withstand voltage level of the system.

For the macroscopic electrode geometries associated with gas-insulated systems, breakdown in compressed SF_6 can be readily accounted for by the streamer theory of breakdown [4]. In addition, the effect of microscopic surface defects upon the system withstand level can be understood by considering discharge growth in the presence of a simple idealized model of a rough surface [5]. It is important to note however that the presence of a stabilizing corona can alter the expected breakdown behavior considerably [6]. In such cases calculations will yield only discharge onset levels.

For practical systems, which inevitably possess a degree of surface roughness, accurate withstand prediction is precluded since a precise knowledge of the associated field perturbations is not attainable. Thus, at best, any protrusion model can but show the trends to be expected in the breakdown/corona characteristic [7]. This limitation with a practical system can be circumvented by the application of a comparative technique based on the figure-of-merit concept [4].

If a detailed knowledge of the breakdown characteristic of a system exists, with for example SF_6 as the insulating medium, then the figure-of-merit concept enables the breakdown response of the system to be deduced for other gases. Rapid assessment of the selected replacement gases is then made possible, which permits gases of particular merit to be identified readily prior to undertaking additional laboratory tests. Figure-of-merit data for a reasonable number of electronegative gases and gas mixtures are available in the literature [8,9,10].

In the present Communication, an experimental verification of the technique is undertaken using gases and gas mixtures selected to allow an examination of the concept over a significant range. A coaxial electrode arrangement with a controlled degree of surface roughness is utilized, and a reference discharge characteristic for this system is obtained with SF_6 as the insulating medium. Discharge onset levels for both electrically stronger and weaker gases are thereafter

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computed from this reference characteristic and the results are compared with experimentally derived data.

DISCHARGE ONSET CALCULATIONS

As mentioned above, the influence of electrode surface roughness on the electrical withstand level of a system can be deduced by examining the breakdown characteristics of simple protrusion models. Such analyses indicate that the practical dielectric behavior of the gas is effectively represented by one specific parameter ratio. The existence of this common ratio led Pedersen to propose that it could be used as a figure-of-merit [11] for strongly electronegative gases, as the values would reflect the sensitivity of each gas to electrode surface defects. In addition, this figure-of-merit M is shown to be re-definable in terms of more simple quantities related to the linear part of the Paschen breakdown curve; viz.

$$M \equiv U_0/(E/p)_{lim}, \tag{1}$$

where, for this part of the Paschen curve, the breakdown voltage U_s can be expressed as

$$U_s = U_0 + (E/p)_{lim}\, pd \tag{2}$$

For strongly electronegative gases or gas mixtures, U_s is observed to be a linear function of the parameter pd for values well above the Paschen minimum [8,9,10].

Furthermore it became evident that, through the figure-of-merit, breakdown or corona onset voltages in a practical electrode system could be calculated for any gas or gas mixture, provided that a reference discharge characteristic was available for that system [4]. In short, if in the same electrode system the discharge onset levels U_A and U_B of two gases A and B are uniquely connected to electron avalanche growth along a particular line of force, then in such a situation discharge onset in gas A is related uniquely to onset in gas B; viz.

$$U_A(p_A) = \frac{M_A(E_A/p_A)_{lim}}{M_B(E_B/p_B)_{lim}}\; U_B(p_B) \tag{3}$$

with

$$p_A = (M_A/M_B)p_B \tag{4}$$

p is gas pressure and $(E/p)_{lim}$ is the limiting field value below which ionizing growth is absent. Consequently, from a knowledge of the functional dependence of U_A with p_A, the construction of a discharge onset characteristic for another gas becomes a simple matter.

APPARATUS AND EXPERIMENTAL TECHNIQUE

The experimental assembly consists of a cylindrical coaxial electrode arrangement. The inner electrode has a radius of 11.0 mm and the inter-electrode spacing is 19.0 mm. The axial length of the constant-curvature section of the outer electrode is 80 mm and that of the inner 450 mm. The overall length of the outer electrode is 160 mm. For the highly stressed inner electrode various surface roughness R_a values [12] in the range 0.1 to 35 μm can be made available although in these preliminary studies surfaces are restricted to R_a=35 μm. This represents a sensible upper limit for a practical system and does not violate the concept of a microscopic perturbation [13]. In addition, this geometry allows the phenomenon of corona stabilization to be exploited over a considerable pressure range [6] such that, with the absence of sparking, possible changes in surface topology are minimized. As discussed, this latter aspect is a crucial factor in the formulation of the comparative approach.

The surface finish of the inner electrodes was produced by a turning process, following which the respective R_a values were determined. Thereafter, but before mounting in the pressure vessel, the electrodes were cleaned in an ultrasonic bath. The vessel was subsequently evacuated to a pressure of ~1 Pa for a period of several hours before filling with the desired gas. Mixtures were allowed approximately 24 hours to achieve a uniform composition prior to measurement. Gas temperatures were in all cases 19.6°C.

Voltages were obtained from a stabilized, SF_6-insulated dc generator, 300 kV/3 mA, and monitored by means of a high precision, high resolution 300 kV measuring system based on a current compensation technique [14]. Discharge onset current pulses were detected oscillographically, and the associated voltage levels were recorded for negative polarity conditions in SF_6, C_2ClF_5, 1,2-$C_2Cl_2F_4$ and an 80/20% SF_6/N_2 mixture. In the case of the mixture, N_2 was admitted first to the pressure vessel. No artificial irradiation was employed, and the applied voltage was raised at ~1 kV/min. The term discharge onset describes the appearance of individual avalanche formations, recorded as discharge current bursts of peak magnitude I~0.1 μA and duration t~2 ms.

For each gas selected, voltage measurements were commenced at the highest gas pressure, the range of which can be determined from a knowledge of the relevant M values. Voltage/pressure characteristics were obtained with a clean electrode mounted at the start of each series. In order to obtain a well-defined discharge onset, each electrode was conditioned initially by running a stabilizing-corona (<I>~100 μA) at the highest gas pressure for a period of ~3 min. An SF_6 control run commenced and terminated each series. This was deemed necessary since the surface topology could change due to sparking at the lower pressures where corona stabilization is lost. Any changes of this nature would invalidate the comparison. The circuit energy available was limited in all cases to <50 mJ.

RESULTS AND DISCUSSION

The first requirement is to obtain for the selected electrode and reference gas a voltage/pressure characteristic for discharge onset. SF_6 is selected as the reference with $(E/p)_{lim}$ and M sensibly constant over the anticipated pressure range; the values are 88.6 kV/kPa•m) and 0.004 kPa•m, respectively. The SF_6 pressure range required to be studied depends on the M of the replacement gas under consideration. For example if its M value is less than that for SF_6 (e.g. ~0.5 $M(SF_6)$), and if its vapor pressure at the ambient temperature is <0.2 MPa, then SF_6 need only be studied at relatively moderate pressures; viz. $0.05<p<0.5$ MPa [4]. As mentioned in [4] gas compressibility effects can be accommodated, but for the gases under consideration in the present study corrections of this nature in [4] will be no more than ~1% over the anticipated pressure range.

The results for discharge onset voltage levels in SF_6 as a function of gas pressure for two electrodes having R_a~35 μm are shown in Fig. 1. In addition to the expected reduction in withstand levels due to surface roughness, a deviation between the recorded data sets is in evidence as gas pressures exceed 0.15 MPa. The repeatability of these data is better than 1%.

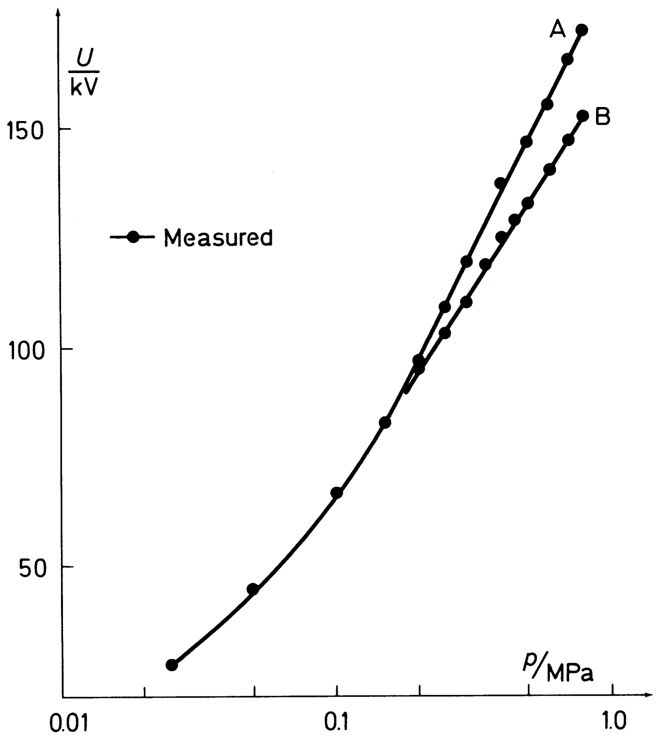

Fig. 1: Discharge onset voltage U in SF_6 as a function of gas pressure p. R_a=35 µm; T~293 K. A and B are the reference onset characteristics obtained with electrodes having nominally equal R_a. M=0.0040 kPa•m; $(E/p)_{lim}$ = 88.6 kV/(kPa•m).

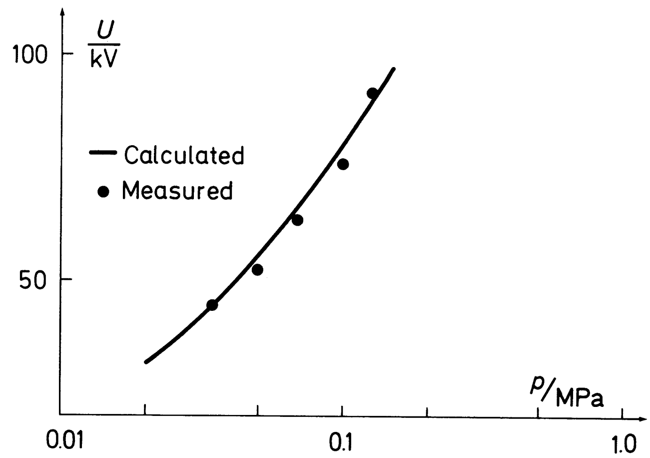

Fig. 2: Discharge onset voltage U in $C_2Cl_2F_4$ as a function of gas pressure p. R_a=35 µm; T~293 K. M=0.0019 kPa•m; $(E/p)_{lim}$=149.2 kV/(kPa•m).

As discussed in [7] the extent of a reduction on onset levels brought about by a rough surface depends on the fraction of the total electron avalanche development which occurs in the perturbed field region. From an examination of simple models a transition at $R_a p_{crit}$~5 Pa•m is expected for SF_6 [15] which agrees with the present observations. The extent of the deviation at any one pressure is controlled thereafter by the field distribution associated with each particular protrusion. Hence for a constant R_a the starting point of the deviation indicates the existence of two distinct pressure domains, and for two nominally identical surfaces (equal R_a) differing field distributions. Consequently, as an expression for the discharge onset voltage as a function of the SF_6 gas pressure is required for each characteristic, it is expedient to subdivide each data set into two groups with p_{crit} as the common limit. For third-order polynomials correlation coefficients of *0.9999* are then readily achieved with standard deviations of less than *1%*.

The results for 1,2-$C_2Cl_2F_4$, C_2ClF_5 and an *80/20%* SF_6/N_2 mixture are presented in Figs. 2 to 4, together with the relevant gas data; see also [8,9,10]. These particular gases were selected on the basis of

(a) 1,2-$C_2Cl_2F_4$, low *M* but high $(E/p)_{lim}$;

(b) C_2ClF_5, single gas, *M* and $(E/p)_{lim}$ comparable with SF_6; and

(c) *80/20%* SF_6/N_2, binary mixture, *M* and $(E/p)_{lim}$ values comparable with SF_6.

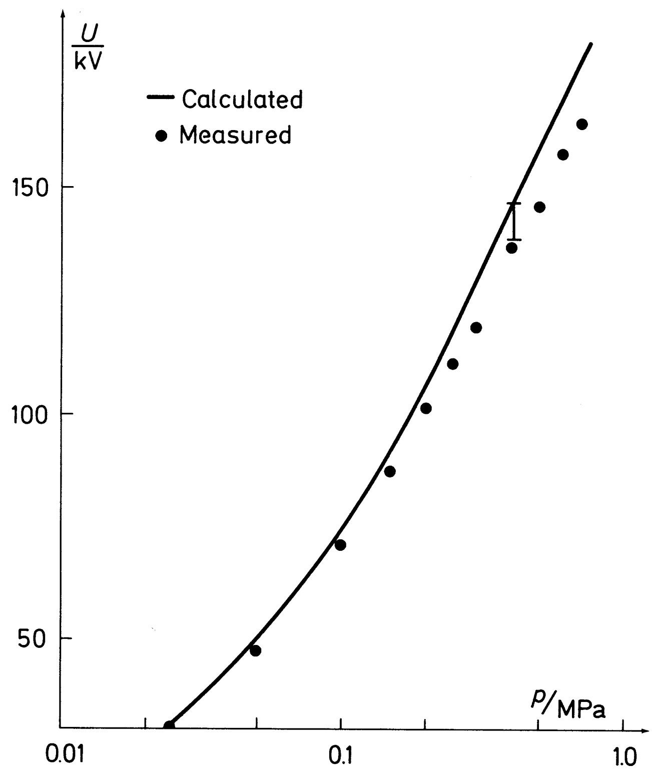

Fig. 3: Discharge onset voltage U in C_2ClF_5 as a function of gas pressure p. R_a=35 µm; T~293 K. M=0.0036 kPa•m; $(E/p)_{lim}$=103.6 kV/(kPa•m).

The data of curve A, Fig. 1, form the basis for the calculated values displayed in Figs. 2 and 3. The curve B data relate to Fig. 4. Agreement to within better than ±*10%* of the measured values is achieved, with the main deviation occurring in the C_2ClF_5 results. The calculated values in this case may be less reliable at the higher pressures due to a pressure dependence of

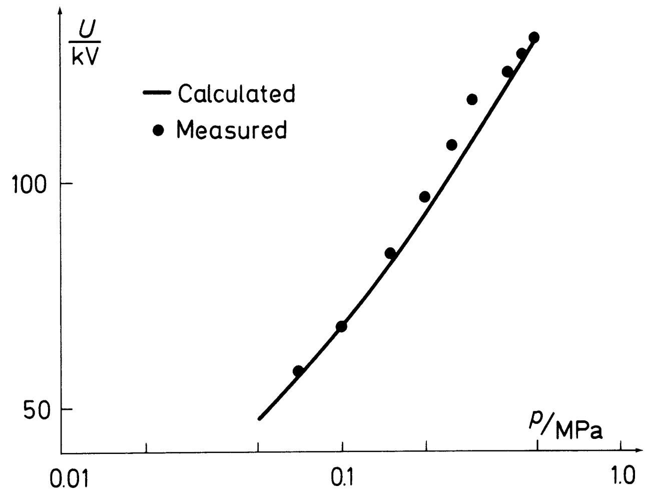

Fig. 4: Discharge onset voltage U in 80% SF_6/20% N_2 as a function of gas pressure p. R_a=35 μm; T~293 K. M=0.0042 kPa•m; $(E/p)_{lim}$=85.2 kV/(kPa•m).

M and $(E/p)_{lim}$. In our laboratory the measurement of M and $(E/p)_{lim}$ are restricted to gas pressures of ≤ 0.1 MPa maximum. The vertical bar in Fig. 3 indicates a calculated lower limit based on an extrapolation from these low-pressure data. It should be noted, however, that the product $M\,(E/p)_{lim}=U_0$ remains relatively insensitive to changes in gas pressure.

These preliminary studies indicate that for a surface roughness environment the figure-of-merit concept forms a promising basis for the evaluation of a new gas or gas mixture. However, it would be more satisfactory if M and $(E/p)_{lim}$ data could be obtained for gas pressures within the range of practical interest, viz. *0.1* to *1* MPa, since the majority of strongly electronegative gases are far from ideal.

Figure-of-merit studies should also be extended to systems where the macroscopic geometry forms the main basis for comparison, since the perturbed fields generated by surface roughness will in certain situations be of secondary importance.

CONCLUSIONS

The figure-of-merit concept for a strongly electronegative gas has been examined for a coaxial electrode system possessing a rough surface (R_a=35 μm). The necessary reference discharge-characteristic is obtained with SF_6 as the insulating medium, for gas pressures in the range $0.02<p<0.8$ MPa. Based on this reference characteristic, discharge onset levels in selected replacement gases have been directly computed through application of the relevant figure-of-merit data. These predicted levels are observed to agree to within better than $\pm 10\%$ of those determined experimentally, and thus the soundness of the concept is confirmed.

The application of this technique could reduce substantially the number of laboratory tests required to be undertaken to evaluate fully the insulating behavior of a proposed replacement gas or gas mixture.

Finally, it should be noted that the figure-of-merit approach encompasses the streamer breakdown criterion, and consequently its application to discharge onset data obtained under impulse conditions must be treated with reservation owing to the inevitable statistical timelag associated with the occurrence of the initiatory electron.

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